Evolutions in U.S. Navy Shipboard Sewage and Graywater Programs

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Abstract

U.S. Navy ships are currently not permitted to discharge sewage (blackwater) in regulated areas throughout the world, including U.S. coastal areas within three miles of shore. Most U.S. Navy ships are equipped with a Type III marine sanitation device (zero discharge) to collect and hold sewage generated in a twelve hour period during transit, and to collect and transfer sewage and graywater to shore facilities when pierside. These systems were backfitted on older classes of ships from 1973 to 1985, and generally provide twelve hours of sewage holding capability during transit. Shipboard sewage has proven to be a harsh and corrosive environment for these systems, however the Navy has accomplished a number of system improvements to enhance the operation, reliability and maintainability of these systems.

In response to the worldwide rising cost associated with the pierside off loading of sewage and graywater, the anticipated future need for U.S. Navy ships to operate for extended periods in littoral waters, and anticipated discharge regulations, the Naval Surface Warfare Center, Carderock Division, in conjunction with the Naval Sea Systems Command, is currently developing shipboard graywater membrane treatment system concepts. As part of this program, modeling and simulation is being employed early in the life-cycle to facilitate research and development efforts for graywater membrane treatment system concepts. These simulations will provide the ability to rapidly modify system configurations, conduct trade off studies, and interactively adjust parameters to predict system behavior in various anticipated operating scenarios.

Introduction

US Navy ships are currently not permitted to discharge untreated sewage (blackwater) in regulated areas throughout the world, including U.S. coastal areas within three miles of shore. As a result, ships are equipped with holding tanks, generally sized to hold the amount sewage generated in a twelve hour period. The exception to this is the DD-963 Class, which is able to burn vacuum collected sewage onboard using vortex incinerators.

Graywater discharge is not routinely regulated, except in the Great Lakes, however there has been increased regulatory interest. Current practice on US Navy ships is to prohibit the overboard discharge of graywater in port provided the ship has the capability to collect and transfer its graywater to pier collection facilities. As a result, costly upgrades to tankage on some US Navy amphibious ships (LHA, LPD-17) are being implemented in order to increase graywater holding times up to thirty-six hours. The reason for these modifications is to support littoral operations. In addition, the cost of off-loading sewage and graywater while in port is expensive and increasing worldwide. In order to combat these rising costs, and to support needs for extended operating times in littoral waters, the Naval Sea Systems Command (NAVSEA), in conjunction with the Naval Surface Warfare Center, Carderock Division (NSWCCD) are developing shipboard graywater treatment systems capable of processing graywater so that clean water is discharged to the environment.

Sewage And Graywater Discharge Restrictions

The discharge of sewage within the littoral waters of the United States is restricted by the Federal Water Pollution Control Act (FWPCA), Section 312 and specified in the Code of Federal Requirements, Title 40, Part 140. Untreated sewage is not allowed to be discharged within three nautical miles of shore; direct discharge is permitted beyond three nautical miles. The restrictions on the discharge of sewage in foreign territorial waters around the world is a little less clear. Discharge is generally prohibited within four nautical miles of shore, but a particular ship must check its Visit Clearance, Status of Forces Agreement (SOFA), Port Guides, or Host Navy Standards for specific restrictions. As for pending future requirements, MARPOL Annex IV, if ratified , would restrict the discharge of sewage within four nautical miles and only allow discharge of comminuted and disinfected sewage within twelve nautical miles of shore. MARPOL designated Special Areas would have the same requirements. It is not known if other countries would impose restrictions other than those called out by MARPOL.

Graywater discharge, which includes wastes from showers, sinks, deck drains, laundries, and galleys (except pulped food), is only prohibited when the ship is pierside, provided the ship has the capability to collect and transfer its graywater to the pier. Currently, most foreign countries have the same restrictions; however, some states have considered restricting discharge of graywater within specific areas, notably Washington State (in the Puget Sound area).

Today's Sewage And Graywater Handling Systems

All of the Navy's surface ships, except the LHA-1 Class, utilize a Type III Marine Sanitation Device (MSD). There are two types of Type III marine sanitation devices. The first is a Type III-A device, and is defined as a "Non-flow-through" device designed to collect shipboard sewage by means of vacuum or other reduced-flush systems and to hold the sewage while transiting navigable waters (0-3 nautical miles from shore). This type may include equipment for shipboard evaporation or incineration of collected sewage. The other is a Type III-B device, and is defined as a Collection, Holding, and Transfer (CHT) system designed to collect both sewage and graywater while in port in order to offload sewage and graywater to suitable shore receiving facilities; to hold sewage while transiting with 0-3 nautical miles; and to discharge both sewage and graywater overboard while operating beyond three nautical miles of shore. This system holds sewage during transits of U.S. territorial waters, usually three nautical miles from shore, while graywater is diverted overboard. Operating in this mode, US Navy ships are designed to have a minimum twelve hour sewage holding capability. When the ship is pierside, both sewage and graywater are collected in the CHT tanks and pumped to the shore discharge connections. These systems were backfitted on older ships from 1973 to 1985 as the result of a Presidential Executive Order. The majority of the Navy's ships have the Type III-B MSD system, however, most of the Navy's newer ships have the Type III-A system with vacuum collection. All of the ships with the Type III-A also have the ability to collect graywater, except the DD 963 and DDG 993 Classes, which will be discussed later. The Type III marine sanitation devices were selected for their simplicity and zero discharge properties. The three basic functional elements that comprise the CHT system are, of course, sewage collection, holding and transfer. The collection element consists of soil and waste drainage mains containing diverter valves. Depending on the position of the diverter valves, sewage or wastewater can be diverted overboard or to the CHT holding tanks. The holding element consists of the CHT holding tank and its supporting equipment. The transfer element includes the sewage transfer pumps and their controls, the overboard and deck discharge piping, and deck discharge assemblies. When the ships are operating outside territorial waters, both sewage and graywater are diverted overboard, except for spaces below the waterline where sewage is still collected by the CHT system and pumped overboard.

The Navy has two basic configurations of Type III-B MSDs based on the size of the system. Systems having a holding capacity of less than 2,000 gallons are only required to have a flow through strainer in the influent line passing through the tank. This system, depicted in Figure 1, allows soil and waste water drains to pass through the tank via an overflow strainer, located inside the tank toward the top. The influent piping then exits the tank and is split into two branches, with each branch flowing through a stop valve, check valve, and inflow strainer to the discharge of the sewage ejector/discharge pump, and then backwards through the pumps into the tank. When the discharge pumps are activated by the tank level indicators to empty the tank, these inflow strainers are back flushed. The majority of these systems are found on the FFG 7 Class and CG 47 Class ships. Navy ship's with Type III MSDs with holding tanks greater than 2,000 gallons are required to have a sewage comminutor installed in each soil main just upstream to the holding tank. A by-pass line is provided to automatically reroute the flow of sewage in the event of a comminutor jam or clog. Any CHT tank greater than 2,000 gallons is also required to have an aeration system to prevent contents from becoming anaerobic and to keep solids in suspension. The aeration system can be of either of two types, a compressed air system or an air aspiration system. The air aspiration system is preferred for tanks less than eight feet in depth. This system consists of recirculation pump which draws sewage from the bottom of the tank and passes it through an aspiration nozzle that mixes the sewage with air from a vent line before it enters the top of the tank. The compressed air system is used for larger tanks as it employs a diffuser system at the bottom of the tank to distribute the air and improve mixing.

Type III MSDs consist largely of pumps, controls and holding tanks. The U.S. Navy's transfer/discharge pumps range in capacity from 9 gpm to 450 gpm, and the Navy's holding tanks range in size from 200 gallons to 50,000 gallons, and each ship generally has at least one forward and one aft system.

The only Type II Marine Sanitation Device that has been used by the Navy is installed on the LHA-1 Class ships. A Type II MSD is defined as a "Flow-through" and "discharge" device that produces an overboard effluent with a fecal coliform count of not more than 200 per 100 milliliters, and total suspended solids (TSS) of not more than 150 milligrams per liter. The unit installed on board the LHAs is a thermally accelerated extended aeration sewage treatment system. After treatment and prior to discharge, the plant effluent is disinfected with chlorine to destroy any remaining pathogenic organisms. The influent

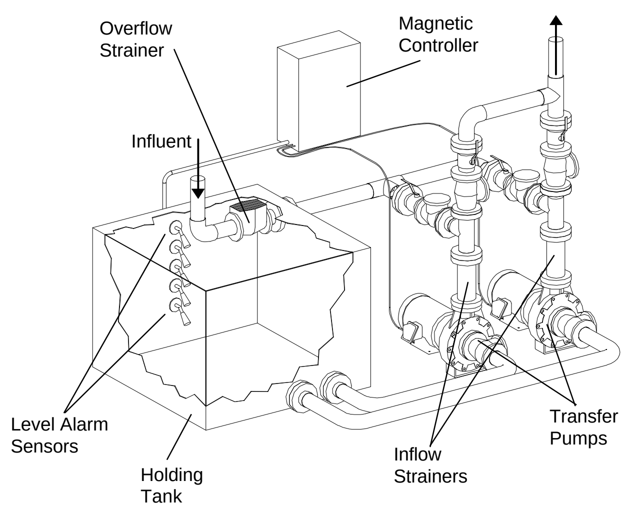

FIGURE 1. U.S. Navy Type III Marine Sanitation Device

box of the plant receives the raw sewage where it is passed through a comminutor to the aeration tank. In the aeration tank, the sewage is mixed with air and heated to facilitate microbial treatment. The liquid is then fed to the sedimentation tank where sludge is allowed to settle out and is returned to the aeration tank. The clear liquid flows to the chlorination effluent holding tank where any remaining pathogenic organisms are destroyed. The effluent is now ready for discharge. The system is designed to achieve maximum effluent discharge standards of 150 mg/liter TSS and 200 colonies/100 ml. The system can be operated continuously, and works best when done so. The Navy has had trouble maintaining the system and operating it in such a way as to maintain consistent effluent quality standards. This can probably be attributed to a lack of continuous system operation. The system cannot simply be turned on when entering coastal waters and instantaneously achieve proper sewage treatment conditions, as it takes some time for a sufficient number of bacteria necessary for aerobic conditioning to develop, especially if the system has lapsed into the septic, non-aerobic condition, or has been inactive.

A second type of sewage collection system, the Vacuum Collection, Holding and Transfer Systems (VCHT) has been used on all of the Navy's newest ships, the DDG 51, DD 963/DDG 993, MHC 51, and PC 1 Classes, except for aircraft carriers. These system still utilize a Type III MSD, but requires significantly smaller holding tanks to achieve the basic 12 hour holding capability. The MHC 51 Class uses this technology to achieve a 5 day sewage holding capability with only an 800 gallon tank, and the LPD 17 ship design uses this technology to achieve a sewage holding time of 36 hours for a ship with over 1,000 people, with smaller tanks than a conventional 12 hour CHT system. As the name implies, these systems use vacuum to collect the sewage, and therefore require much less flushing water than a conventional water closet. Vacuum water closets use approximately 3 pints of water per flush versus conventional water closets which use approximately 4 gallons per flush (32 pints), which translates to a 90% reduction in sewage waste. VCHT systems on U.S. Navy ships use a separate graywater collection system, however a common holding tank can be used, especially on new systems where the holding tank is not under vacuum. However, all the current VCHT ships do have separate graywater holding tanks, although the DDG 51 can divert graywater influent to the VCHT sewage tank for common discharge when pierside or at sea. One big advantage of a VCHT system is that it allows much more flexibility in the way piping is run. Pipe runs no longer have to maintain a continuous downward slope, in fact the vacuum collection piping can have a maximum lift of 15ft, or a series of lifts totaling 15 ft in each piping run. It is preferable to keep a gradual downward slope in the runs between lifts, and to keep the rising parts (lifts) basically vertical. Cleanouts are required every 50-60ft, and these also serve as reformer pockets to reform the sewage slug. All of these factors result in a system that requires less weight and less space, provides more design flexibility, and reduces sewage disposal costs by a factor of ten.

GRAYWATER COLLECTION

U.S. NAVY ships are required to collect and transfer graywater to the pier for disposal, if equipped with the ability to do so. This requirement stems from OPNAVINST 5090.1B "Environmental and Natural Resources Protection Manual" (Sect. 19-3.4.1). This requirement, in turn, stemmed from the attempts by some states to regulate this discharge from ships under that state's implementation of the Clean Water Act (CWA) and their water quality standards. It has been the Navy's policy to give all of its ships the ability to collect and transfer graywater when pierside. Presently, all of the Navy's ships have the ability to collect and transfer graywater to the pier, except four of the LHA 1 Class ships and four of the DD 963 Class ships. The LHA Class ships are receiving Ship Alterations (SHIPALTS) to give them the capability to collect and transfer graywater. The LHA 3 was completed in 1997, and the follow-on LHA ships are scheduled to receive a Mid-Life CHT Upgrade SHIPALT, which will give them the capability to collect and hold sewage and graywater for 36 hours. Thirty-one of the thirty-five DD 963/ DDG 993 Class ships have received their Graywater Collection SHIPALT, but the remaining four were not done because of their specific ship life cycle issues.

Ships equipped with the standard Sewage CHT system have some built-in graywater holding capability, but it comes at the expense of reduced Sewage holding capability. Generally these ship have sewage holding tanks designed to provide a twelve hour sewage holding capability, but graywater can be diverted to the tanks and held there also. Since the graywater and backwater shipboard generation rates are approximately the same, 30 gallons per man per day, diverting and holding ships graywater for one hour will reduce the ship sewage holding capability by one hour, resulting in a combined sewage and graywater holding time of only six hours. Unfortunately,for those ships with particularly long coastal transits, this is not a sufficient amount of holding time.

Ships equipped with the Navy's Sewage VCHT systems, while they have greater sewage holding time, have small separate graywater collection tanks, which are only meant to serve as surge tanks to provide graywater shore transfer capability. The LPD 17, although a VCHT system, will have separate graywater holding tanks to provide a twelve hour holding capability.

RELIABILITY AND MAINTAINABILITY ISSUES

The Navy is constantly trying to improve the reliability, maintainability and ease of operation of its shipboard sewage systems. This is largely due to the nature of sewage itself. Sewage is highly corrosive, especially when it becomes septic and anaerobic bacteria begin to generate hydrogen sulfide and sulfuric acid. Sulfuric acid obviously adds to corrosion problems, but hydrogen sulfide and other gases, as well as pathogens in the sewage create serious health and safety concerns. Hydrogen sulfide in sufficient concentrations is deadly and quick acting. The health and safety issues require the sewage CHT system to be a zero leakage system, and the corrosion, clogging and scaling problems make it hard to achieve the desired reliability and ease of maintenance. Sewage collection piping and tanks are subject to scaling and corrosion, sewage pumps are subject to clogging, leakage and corrosion, and the tank level sensors, (pump control sensors) are subject to fouling and degradation.

Sewage collection piping is subject to scaling and corrosion. The primary form of scale is calcium carbonate, and is particularly a problem in urinal piping where periodic use causes deposits of calcium and urinal salts to be deposited quickly. The Navy is currently evaluating a waterless urinal that deposits a very soft scale in reduced amounts. The urine passes through a lighter than water substance that prevents hard scaling, and also serves as a vapor trap. This fluid has to be replenished on a periodic basis. Although this reduces the generation of sewage waste, the real benefit is that the scale that develops in the piping can be removed by flushing with water at firemain pressure. Seawater corrosion, augmented by sewage, of CHT piping is a particular problem on the CHT discharge piping, especially on Aircraft Carriers. Aircraft Carriers have a horizontal discharge header that allows them to pump sewage from the various holding tanks to the various discharge connections. Unfortunately, this loop creates pockets and flat areas where sewage can accumulate and corrode the piping, especially if it goes septic. The Navy has coated the discharge piping on Carriers with three coats of Naval Research Laboratory (NRL) NRL 4B 100% solids epoxy. Typical total coating thickness is between 15-20 mils. This coating has been very effective in reducing pipe corrosion. A normal section of 90/10 copper/ nickel discharge pipe on carriers had a life expectancy of three years, whereas the epoxy coated pipe is expected to average a seven year life. The only disadvantage is that the epoxy coated pipe is more difficult to repair and is damaged by hot work.

The clogging of sewage pump suction and discharge gauges by the accumulation of solids in the process connection which the gauge attaches to, has been an operational problem. This problem has been eliminated by the use of ring gauge isolators. These resemble a silicon fluid filled donut held in a flangewith the pumped fluid flowing through and contacting the inside. The gauge is attached to the donut, and changes in pressure move the fluid in the donut, which actuates the gauge.

A large CHT system reliability and maintainability problem is sewage pump seal failures. Sewage pumps are required to have zero leakage mechanical seals. The pumps are designed to Military Specification, MIL-P-24475 requirements, and have double mechanical seals meeting the requirements of ASTM F 1511-95. Unfortunately these pumps and seals have experienced high failure rates. This is due to several factors, including poor installation, poor operation, and the zero leakage requirement itself. The seal will fail when run dry or dead headed, which could be caused by a failed cutout tank float switch, clogged line, or improper valve alignment. The seals themselves are very sensitive to proper alignment with the shaft and one another. They are also sensitive to lands, ridges, scrapes, grease, and even finger prints on the seal faces. So, care and attention to detail is required to properly replace the seals, which is difficult to achieve with deck plate repairs. The other problem with longevity is the zero leakage requirement itself, which requires the seal to be replaced when any sewage leakage outside the casing is detected. This fix is necessary for health reasons, but for othermechanical seal applications, the seal can operate normally for most of its seal life with a small amount of leakage. The U.S. Navy has developed a Machinery Alteration, MACHALT 469, which adds pump under-current and over-current monitors in the pump controllers to shut the pumps off if a dead head or no-load condition is detected. Whereas the pump thermal overload will shut the pump off before the motor is damaged, these are designed to shut the but off before the seals are damaged, there by reducing maintenance and improving reliability. There are also other efforts aimed at improving the seal design. Many of the U.S. Navy’s Aircraft Carriers have been back-fitted with a new type of tornado effect sewage pump, which uses a large cartridge seal incorporating a grease packed labyrinth seal that is charged with low pressure air. The seal is designed to leak approximately 0.5 CFM of air into the volute, this prevents sewage from leaking the other way, such that a worn-out seal can be detected by excessive air leakage before it leaks sewage into the compartment. (Johnson, Myers, Schepis, Crew, and Keltner 1997) This seal has worked very well as a zero-leakage seal for the large (300 GPM) Aircraft Carrier sewage pumps. NAVSEA is also working to provide a more robust replacement seal for its existing sewage pumps. A twin cartridge double mechanical is currently being tested.

Tank level sensor failure has been a persistent maintenance problem for Navy Ships. These failures can result in damage to the transfer pumps, by running them dry when the pump cut-off switch fails, and can result in tank overflows when the pump cut-in switch fails. The most common mode of failure for the standard mercury float switch is water intrusion between the float material and the cable jacket, which corrodes and shorts out the switch contacts. The second most common mode of failure is the failure of the cable and cable jacket itself due to repeated bending and the corrosive sewage environment. The Navy has addressed these problems by requiring an improved mercury float switch with resin potted switches, and has a vigorous test and evaluation program involving four different point level sensors, two continuous tank level indicators, and five different types of cables, all commercially available. These switches include mechanical, magnetic, ultrasonic, electrical conductance, electrical resistance, and mercury switch technologies.

Last, but not least, is the issue of the longevity of the sewage holding tank itself. In order to minimize maintenance cost the desire is to have a tank coating that at least matches the ship dry-docking availability cycle, currently averaging seven years. NAVSEA has started to specify Phenolic and Novolac epoxy coatings in order to achieve the desired lifecycle. The Phenolic coating is currently being evaluated on the USS ABRAHAM LINCOLN (CVN 72). In concert with the new coatings, new tank preparation and coating application procedures are being developed, as this is critical to obtaining a successful coating system. Also, the U.S. Navy is now specifying GRP (fiberglass) piping and ladders for use inside the CHT tank, as this material holds up extremely well in the sewage environment.

GOALS FOR THE FUTURE

- The Chief of Naval Operations, through its Environmental Protection, Safety and Occupational health Division (N45), has a vision for Environmentally Sound Ships of the 21st Century, whereby new-design ships must be able to operate in U.S, international, and foreign waters in compliance with environmental laws and regulations without degradation of mission or quality-of-life. This means that (1) ships must be designed and operated to minimize waste generation and optimize waste management and (2) shipboard systems must be used to destroy or appropriately treat wastes generated onboard. Commanding officers of Navy ships operating in the 21st century must be able to carry out any mission and visit any port worldwide without concern about waste discharge or offloading problems, arising from national or local requirements. Furthermore, Navy ships must minimize or eliminate their reliance on capital and labor intensive shoreside waste disposal facilities which are not available throughout the world. (Nickens, Pizzino, and Crane 1997) The vision can be simply stated as "the Navy will operate ships that do not create any environmentally harmfully discharges".

In support of these goals, the Navy is developing Sewage and Graywater treatment systems that provide independence from shore facilities, can be integrated with other waste destruction systems, and produce an environmentally benign discharge.

New Sewage And Graywater Treatment System Concepts

Numerous conventional sewage and graywater treatment processes have been evaluated by NAVSEA for their ability to meet U.S. Coast Guard Type II MSD effluent quality requirements, as well as the operating requirements of naval combatants. However, most of these processes were determined not to be capable of meeting Type II MSD effluent quality requirements with U.S. Navy sewage or suitable for U.S. naval shipboard use. The confined space available to install, operate, and maintain these conventional treatment systems, low manning available for maintenance, and safety issues related to the storage and use of caustic, corrosive, and flammable chemicals required by the treatment processes make these systems undesirable for naval shipboard use.

Sewage and graywater are both high strength waste streams (Biochemical Oxygen Demand (BOD): 700-2500 mg/L and Total Suspended Solid (TSS): 300-1300 mg/L) composed of organic and inorganic particles and dissolved organic matter (e.g., starches, proteins, carbohydrates). Conventional filtration processes (e.g., media bed, strainers) are capable of removing the suspended matter to MSD Type II levels, but require frequent backwashing or filter media replacement. In addition, the large majority of methods capable of removing fecal coliform bacteria rely on biologically toxic chemicals which result in safety concerns for both the sailor and the aquatic organisms found in the receiving water body.

Working with non-oily waste water effluent discharge goals of TSS of 100 mg/liter, BOD of 50 mg/liter and Fecal Coliform of 200 colonies/100 milliliters in mind, a recent world-wide survey of industry for technologies suitable for the shipboard graywater and sewage treatment identified two technologies considered mature enough for evaluation and development: membrane filtration and evaporation. The evaporative process was subsequently evaluated in the laboratory with graywater. Results showed that the system could not reliably meet effluent discharge goals and was far too large for naval shipboard use. Membrane ultrafiltration was subsequently evaluated and is currently under development.

Membranes are essentially thin barriers or films of material that allow certain substances to pass while rejecting others. Membranes that allow only some substances to pass through them are called semipermeable membranes. Most commercially available membranes are made from polymers, ceramics, metals, or porous materials impregnated with liquid or gelatin-like substances. Those membranes contain a large number of small holes (pores) through which the solvent and other small molecules, ions, or particles can pass. As with conventional filtration systems, membranes typically operate at room temperature.

Membranes provide a straight-forward and relatively simple means to separate and concentrate waste streams (up to 98%), and thereby decrease waste volumes and provide the opportunity to substantially increase holding times. Additionally, membrane systems require less space and power than phase-change processes such as vaporization, are relatively inexpensive, and have many components in common with other shipboard mechanical systems. The U.S. Navy has previously evaluated membrane concentration of naval wastewaters. In 1977, researchers found that ultrafiltration was an effective process for treating raw sewage and activated sludge wastes, and for producing an effluent that met Federal discharge standards for total suspended solids and fecal coliform. These evaluations reported, however, that the membrane materials evaluated (mostly cellulosic) were not durable and suffered rips and leaks. They also were not rigorous enough to withstand harsh cleaning procedures required to restore their performance. New membrane materials and manufacturing techniques have been developed during the intervening 15 years which justified re-examination of membrane technology.

MEMBRANE SYSTEM PROTOTYPE TESTING

Laboratory and pierside membrane prototypes treatment systems have been developed and tested processing graywater. These systems have been evaluated both in the laboratory, using Navy-generated land-based graywater mixtures, and pierside at the Norfolk Naval Base. A notional graywater membrane treatment system configuration is depicted in Figure 2. These systems show promise and are currently undergoing advanced engineering development for installation aboard 21st Century Naval combatants. The first stage of the system uses large-bore polymeric membranes to trap coarse and fine solids and to remove a significant amount of biochemical oxygen demand (BOD) and fecal coliform bacteria. In order to avoid environmentally undesirable doses of chlorine, an enclosed ultraviolet light reactor is being used to ensure disinfection of the ultrafiltration membrane effluent. Aerobic conditioning in conjunction with membrane filtration is also being evaluated. The aerobic conditioning will reduce the soluble organic content of the feed to ensure that all anticipated 21st Century effluent discharge goals will be met.

A first-generation three gallon per minute treatment system was demonstrated successfully in the laboratory using Navy-generated land-based graywater mixtures. The first stage of the system used large-bore (3/4" diameter) polymeric membranes to trap coarse and fine solids and to remove a significant amount BOD and fecal coliform bacteria. A second-stage nanofilter enabled the system to remove dissolved organics and further reduce the effluent concentrations of BOD and suspended solids. Subsequently, a three gallon per minute prototype unit was evaluated for 850 hours pier-side at the Norfolk Naval Base using graywater from the USS L.Y. SPEAR.

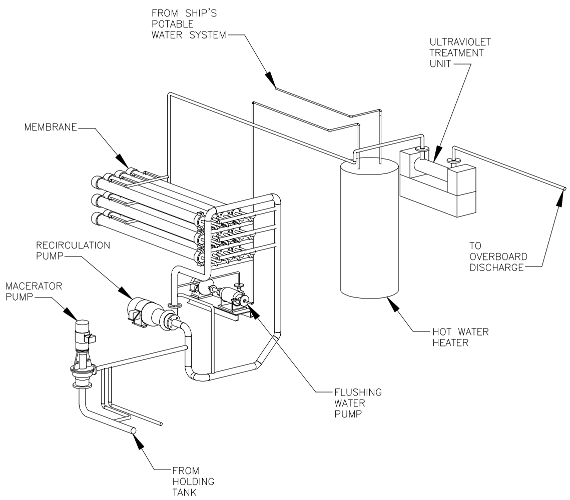

FIGURE 2. Typical Graywater Membrane Treatment System Configuration

Using the graywater systems as a base-line, a non-oily wastewater treatment prototype was developed. The first stage of the system used the same large-bore polymeric membranes. The second-stage nanofilters were replaced with an ultraviolet (UV) light reactor to ensure disinfection of the ultrafiltration membrane effluent. Tests were conducted on non-oily wastewater (combined sewage and graywater) from ships while pier-side at Norfolk Naval Base. The prototype unit was evaluated for 830 hours. Results showed that wastewater treated by this membrane system shows promise of meeting anticipated U.S. and International discharge standards for sewage and graywater. While aeration of the feed tank provided some bio-conditioning of the wastewater, the conditioning was insufficient to meet effluent quality goals for BOD, due to short hydraulic retention times. However, the membrane-based prototype was able to meet effluent quality goals for total suspended solids and fecal coliform bacteria. Stable membrane performance was achieved by the introduction of air to the feed tank; without aeration of the feed, it was found that membrane throughput decreased rapidly over 120-hours to one-quarter of the initial throughput. Fouling of the UV reactor quartz jacket and subsequent poor disinfection performance was mitigated by high velocity flushes of the reactor, daily sterilization with chlorine bleach, and weekly mechanical cleaning.

Dynamic Simulation Of Membrane Treatment Systems

Modeling and simulation is being employed early in the graywater membrane treatment system life-cycle in order to supplement research and development efforts. These efforts include the utilization of a commercial real-time simulation software package, which provides the ability to rapidly modify system concepts and interactively adjust parameters in order to predict system behavior under various anticipated scenarios. The resultant system concept simulations can then be used to conduct design and trade-off studies for the ultimate design of platform specific graywater treatment systems

SIMULATION SOFTWARE

A commercial simulation software package (SIMSMART™) capable of producing real-time dynamic simulations of piping systems was selected. Real-time dynamic system simulation of piping systems allows engineers to interactively adjust system parameters and immediately observe system responses. This provides the capability to rapidly modify system concepts and experiment with alternative approaches. This also provides the capability to predict system performance in "off-design" conditions due to abnormal loads, component failure, or equipment casualties.

The particular simulation package chosen provides the capability to build piping networks using graphical tools as well as perform physics-based flow network analyses in real-time. This type of simulation is different from many other types of simulation based design in that the computer does not display three-dimensional objects moving in a virtual world. While the software does not provide visualizations of internal fluid conditions, pipe movement due to stress, and shock or vibration, it does simulate operation of the system by displaying parameters such as flow rates, tank levels, pump operation, valve position, and system pressures and temperatures at various locations within the network (Reynolds, Kloetzli, and Schuler 1996).

The primary simulation interface consists of a two-dimensional schematic of the system flow and the physical system data required to simulate operation. This schematic is comprised of a network of interconnected icons which represent pipe, equipment, and digital and analog controls. A typical system schematic for a graywater system, as displayed by the simulation software, is depicted in Figure 3.

While the simulation software contains a vast component library of marine and fluid flow equipment such as valves, pipes, pumps, tanks, level transmitters, pressure gages, flow transmitters, etc., membranes were not part of the library. As a result, a component model based on first principle physics had to be developed to simulate the functional performance of membranes in the cross-flow ultrafiltration process.

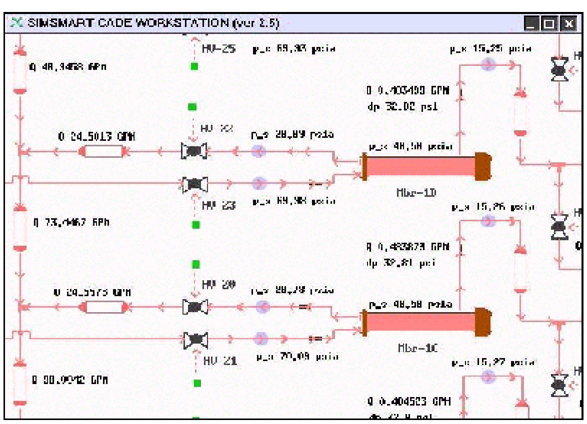

FIGURE 3. Graywater Membrane System Schematic, as Displayed by the Simulation Software (SIMSMART^{TM})

MEMBRANE PHYSICAL PROCESSES

Ultrafiltration, like reverse osmosis, is a pressure driven separation process in which a solution is moved across a semi-permeable membrane. The result of this process is a high-quality solution stream, referred to herein as "permeate", and a concentrated waste water stream, referred to herein as "concentrate". The difference between ultrafiltration and reverse osmosis is primarily based on the particle size of the permeating species, the mechanism of rejection, the relative magnitudes of the permeate flux, and the pressure difference across the membrane (Wiesner and Chellam 1992). For example, ultrafiltration is independent of osmotic pressure[1], and occurs when particle size is relatively large, whereas reverse osmosis is dependent upon osmotic pressure, and occurs when particle size is relatively small. Additionally, ultrafiltration can be effective at pressure differentials between 5-100 psi (34-688 KPa), whereas reverse osmosis typically is effective at higher pressure differentials. Furthermore, "solute-membrane chemistry plays an important role in determining the rejection of soluble species by reverse osmosis membranes" (Wiesner and Chellam 1992).

There are two operational modes commonly used in cross-flow ultrafiltration membrane processes, "feed and bleed" and "dead-end"batch. In the feed and bleed mode, a concentrated waste stream is being continuously generated; while in the dead-end mode, a concentrated waste stream is generated only when backflushing occurs. In both cases, a buildup of rejected particles (or cake layer) forms on the membrane surface causing a time decaying total permeate flux profile. For feed and bleed processes, there is a steady-state time from which the total permeate flux is constant, as the buildup effect is limited due to the main

[1] When two substances separated by a membrane have different chemical potential (due to a difference in concentration), then the Osmotic Pressure is the pressure of the substance that has the lower chemical potential necessary to equalize the system.

flow being parallel to the membrane surface (hence the name cross-flow ultrafiltration). This causes the cake layer thickness to be independent of time, and a function only of position within the membrane flow channel. As a result, feed and bleed processes have a steady state region which ultimately leads to a constant total permeate flux. For dead-end processes, there is no steady state region, thus the total permeate flux profile always decays with time. Figure 4, depicts typical permeate total flux profiles of both the cross-flow ultrafiltration and dead-end batch modes.

As mentioned above, cross-flow ultrafiltration has two distinct permeate flux profiles, one time-dependent and one steady-state. During the transient state, the concentration of solute and the solvent diffusivity at the membrane wall will increase and decrease respectively with time and position as solvent permeates throughout the membrane. When the concentration at the membrane wall reaches its maximum value or the gel concentration[2], a cake layer of rejected particles will begin to form at the membrane wall.

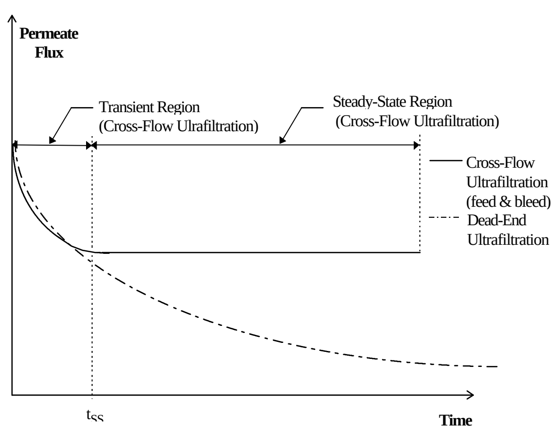

FIGURE 4. Typical Permeate Flux Profiles for Cross-Flow Ultrafiltration and Dead-End Modes

[2] Concentration at which a cake layer starts to form on the membrane walls.

This cake layer will grow with time until steady state conditions are achieved, which creates a time decaying total permeate flux profile during the transient state. When steady-state conditions are achieved, cake layer thickness becomes only a function of position rather than time. This behavior occurs because "at steady state, the volumetric flow rate at which particles are convected towards the channel exits in the polarized layer at an axial location x is balanced by the volumetric rate at which particles are deposited into the layer from the channel entrance up to x " (Wiesner and Sethi 1994).

A cross sectional view of a typical cross-flow ultrafiltration membrane operating under steady-state conditions is shown in Figure 5(a). This figure depicts a membrane region where there is no buildup of rejected particles. This region is referred to as the "entrance length", and is defined as the axial distance from the membrane entrance to a critical point, where the solute concentration at the wall reaches its maximum value and the cake layer begins to form. Beyond the critical point, cake layer thickness will grow with axial distance.

The behavior of the steady-state permeate flux profile within the membrane is depicted in Figure 5.(b)[3]. Note that the permeate flux between the membrane entrance and critical length is considered constant. This is attributed to the fact that no cake layer is formed within this region; and consequently, the permeate flux is only limited by the resistance of the membrane itself. However, this is only true if it is assumed that the solute concentration, and therefore, the diffusivity at the membrane wall, does not change significantly within the entrance region. This constant permeate flux, called the "permeate flux for clean water", is provided by membrane

[3] Note that although the permeate flux profile shown in this figure decays with axial distance, the overall membrane permeate flux is still constant with time; which is consistent with the behavior of the permeate flux profile for cross-flow ultrafiltration depicted in Figure 4.

manufacturers, and is obtained experimentally using clean water as feed water. Also note that the permeate flux between the critical length and membrane length has a decaying behavior due to the cake layer presence and its increasing thickness with axial distance.

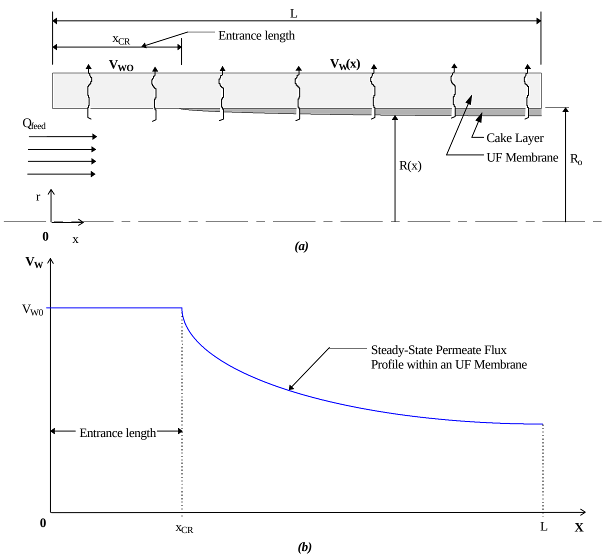

FIGURE 5. ***(a)*** **Cross Sectional View of a Typical Cross-Flow Ultrafiltration Membrane Operating Under Steady-State Conditions.** ***(b)*** **Corresponding Behavior of the Steady-State Permeate Flux Profile**

ALGORITHM DEVELOPMENT

Once the membrane physical processes were defined mathematically, development of a computer algorithm defining overall membrane behavior was required in order to generate appropriate computer code for incorporation into the simulation. The main steps of the cross-flow ultrafiltration algorithm developed for the subject membranes are shown in Figure 6.

In order to solve the cross-flow ultrafiltration algorithm, numerical integration and root finding techniques are required. However, the expansive iterative process involved, coupled with the complexity of the equations in the ultrafiltration model, may inhibit processor operation to a point where real-time simulation is not possible. Therefore, mathematical manipulation and optimization of the more complex equations are necessary so that a relatively quick algorithm can be obtained, which will lead to calculation speeds suitable for real-time simulations.

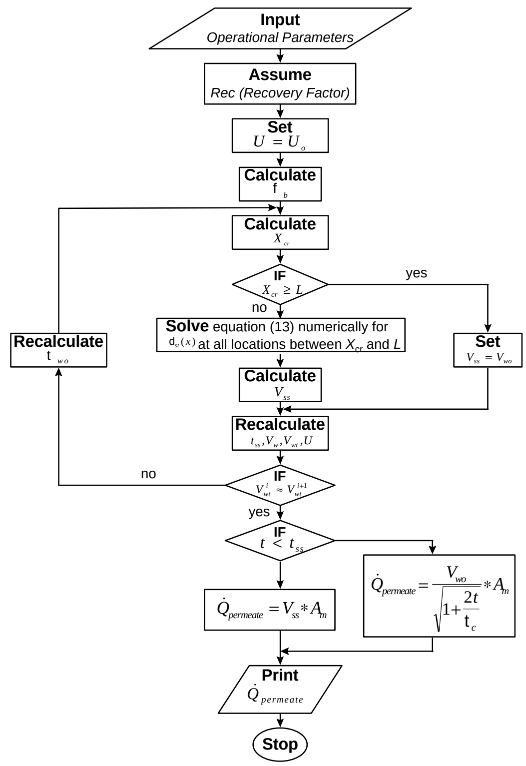

FIGURE 6. Cross-Flow Ultrafiltration Membrane Algorithm

INCORPORATION OF MEMBRANE ALGORITHM INTO THE SIMULATION SOFTWARE

After the ultrafiltration membrane algorithm is created and optimized, it must be incorporated into the simulation software package. This incorporation will first require an understanding of the particular simulation engine used and the language it understands.

Simulation engines generally run routines that control and manage a simulation network. These engines also call other routines to perform calculations and obtain solutions for entire simulated system networks at every simulation time unit. The simulation engine calls a routine that scans all system icons and extracts their resistance, or energy level, every i^{th} simulation loop or cycle. Based on this information, it creates a system energy conservation matrix which it then solves in order to obtain the solution of the $i^{th}+1$ simulation loop of the entire piping network system.

Essentially, the simulation software "sees" the entire simulated system as a number of resistances connected in series to form sections, which in turn are connected by nodes to form a network. Within the network, the simulation software also identifies points where a given amount of energy is added to the system. As a result, the simulation software classifies objects into one of three categories:

- *Objects that produce resistance to flow (pipes, valves, orifice plates, etc.)*

- *Objects that add given amounts of energy to the network (pumps (kinetic energy), tanks or fixed pressure inputs and outputs streams (potential energy))*

- *Objects that diverge or converge flow (tees, junctions, etc.)*

The implementation of the ultrafiltration membrane algorithm into a network solver software required the usage of two of the above categories. A cross-flow ultrafiltration membrane can be simulated or represented by an equivalent model composed of a three stream junction and three special sections, one for each stream. The three stream junctions simulate the flow separation process that occurs in a real membrane. The special sections, located at each junction stream, simulate flow resistance caused by the membrane wall through which fluid permeates, and by the membrane internal channel through which concentrate flows. The membrane equivalent model is depicted in Figure 7.

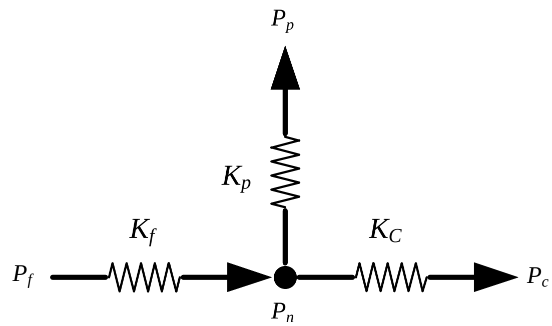

FIGURE 7. Membrane Equivalent Model

Once all quantities of the equivalent membrane model are defined, an algorithm that integrates the equivalent model into the simulation software piping network system and establishes the communication and variable transfer between the membrane model and the network solver routine is needed. Figure 8 shows the fundamental algorithm that integrates the membrane algorithm into the network solver via the membrane equivalent model described above. This algorithm is composed mainly of two parts: an initialization function, and an execution function.

The initialization function is called once by the network solver routine during a simulation. Input parameters are read from a data file, and the initial values of the feed, concentrate and permeate side resistance are calculated. After the initial values are calculated, they are transferred to the network solver routine so initial pressures, flow rates, velocities, etc. at every point in the entire system can be calculated and displayed accordingly.

The execution function is called every simulation loop once the initialization cycle is complete, and begins reading the pressure and flow rate of the i^{th} simulation loop at the membrane feed, concentrate, and permeate sections. With these values and some other values read from a data file during the initialization cycle, the ultrafiltration membrane algorithm is executed and the membrane permeate and concentrate flow rates are calculated respectively. These flow rates are transformed into resistance using Darcy's law, which are then transferred to the network solver routine so that the solution of the entire network system for the $i^{th}+1$ simulation loop can be obtained. This cycle is repeated for the duration of the simulation.

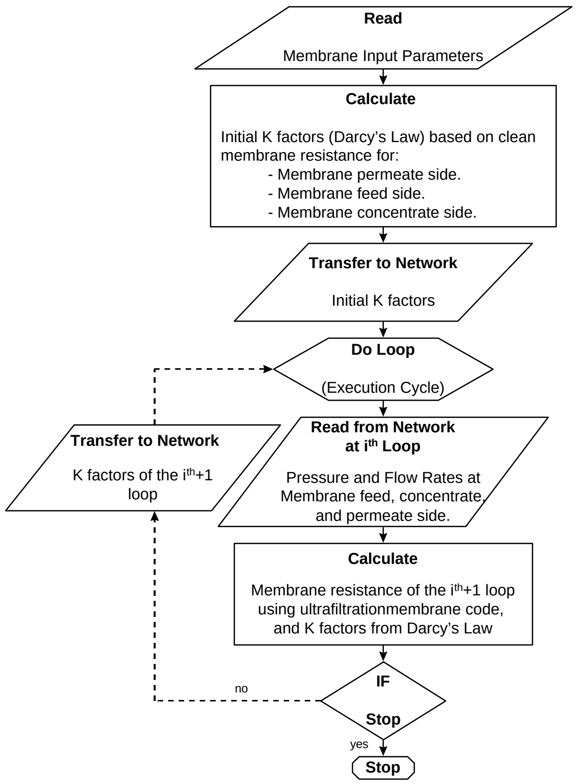

FIGURE 8. Membrane Model/Network Solver Integration Algorithm

SIMULATION RESULTS

In order to test the cross-flow ultrafiltration algorithm, an existing prototype graywater membrane system was modeled using the real-time simulation software. Simulation results indicate that the order of magnitude of membrane output values and the flow stability behavior of the membranes correspond to expected values based on laboratory performance data. In addition, the time required to solve the membrane models was satisfactory for real-time simulations within one second, that is one second of simulation time was equal to one second of actual time.

CURRENT AND FUTURE SIMULATION APPLICATIONS

NSWCCD is currently conducting laboratory evaluations (LABEVALS) of prototype graywater membrane treatment systems for use aboard US Navy ships. As part of this effort, dynamic simulations of select prototype systems are being performed in parallel. This provides the ability to predict system performance and determine system modifications prior to equipment fabrication. Comparisons of laboratory test data and simulation data are also being performed in order to validate simulation models.

With this simulation capability, future uses include performing design and performance trade-off studies of various system configurations. Essentially, existing shipboard graywater collection systems can be modeled with proposed membrane treatment systems incorporated. This provides a means to optimize membrane system design for particular ship configurations and perform trade-off studies for varying options. The simulation will provide performance data to determine if a particular configuration will meet the desired treatment criteria. Once this is determined, estimated system costs can be derived from the component data. For example, simulation data may reveal that a particular size pump is required to meet required treatment flow rates. Data for this pump, including its cost, can be entered into the simulation accordingly. Resulting cost data associated with the specific configuration can then be extracted along with simulation performance data.

In addition to design/performance trade-off studies, shipboard feed-stream analyses can be performed using dynamic simulations. This facilitates determining the periodicity and duration of membrane system operation based on shipboard graywater generation. For example, high periods of graywater generation, such as scullery uses after meal periods and laundry operations, can be simulated to determine necessary membrane system operation cycles. The simulation can also be used to analyze the effects of specific graywater compositions during the peak cycles. This is accomplished by varying particle size, concentration, etc. corresponding to a particular feed stream combination.

Future shipboard graywater membrane treatment systems will be controlled by Programmable Logic Controllers (PLC) integrated with a Graphical User Interface (GUI) or touch panel. When the operator executes a command via the GUI, it is translated by the PLC to a signal which operates system equipment accordingly. In lieu of connecting the PLC to actual equipment, it can be connected to the simulation software. This facilitates programming and testing of control equipment without actually operating the system, or fabricating a system for this purpose.

In addition to the programming and testing benefits, virtual prototype training can be accomplished as well. For example, an operator can be stationed at a membrane system control GUI, which is connected to the simulation software. An instructor can then induce specified operating scenarios via the software and evaluate the operator's performance.

Conclusion

Since U.S. Navy ships are currently not permitted to discharge raw sewage in regulated areas, and graywater discharge is of regulatory concern, significant constraints may be placed on the operation and mission duration of US Navy ships in littoral waters. In response to these constraints, and the worldwide rising cost associated with the pierside off loading of sewage and graywater, NSWCCD and NAVSEA are currently developing shipboard graywater membrane treatment system concepts. As part of this program, modeling and simulation is being employed early in the life-cycle to supplement research and development efforts. These simulations will provide the ability to rapidly modify system concepts and interactively adjust parameters to predict system behavior in various anticipated operating scenarios. The resulting system concept simulations can then be used to conduct design and trade-off studies for the ultimate design of platform specific non-oily wastewater treatment systems, perform feed-stream analyses for varying wastewater generation scenarios, facilitate PLC programming and testing, and provide a means to train system operators.

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